Heating of the Solar Wind Beyond 1 AU by Turbulent Dissipation

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Abstract. The deposition of energy into the solar wind beyond 1 AU is thought to result from the dissipation of low frequency magnetohydrodynamic (MHD) turbulence via kinetic processes at spatial scales comparable to the ion gyroradius. Beyond 1 AU, solar wind turbulence is comprised of both a decaying component generated in the corona and turbulence generated dynamically *in situ* by processes such as stream shear, interplanetary shocks, and, beyond the ionization cavity, the pickup of interstellar neutral atoms. A turbulence-theoretic model describing the radial evolution of the power in magnetic fluctuations in the solar wind has been developed recently and the predictions were compared successfully with Voyager data. Using the dissipation rate predicted by this model, we evaluate the expected heating of the solar wind by MHD turbulence. The effective adiabatic index of the solar wind is reduced from 5/3 and the theory accounts for the apparent heating of ions in the outer heliosphere.

INTRODUCTION

Low frequency fluctuations in the solar wind plasma represent perhaps the most extensively studied type of magnetohydrodynamic (MHD) turbulence, having been observed by spacecraft instruments for more than thirty years (1, 2, 3). The observed turbulence displays properties expected of both hydrodynamic and MHD theory, including distinctive spectra and correlations (3, 4).

Substantial fluctuation energy resides in the inferred range of spatial scales between the ion inertial scale ($\approx 10^4$ m at 1 AU) and the observed correlation scale ($\approx 6 \times 10^9$ m at 1 AU). This spectral range and the larger energy-containing scales provide a significant reservoir for the heating of thermal particles if that energy can be transported to the small scales where wave-particle interactions are most efficient. Observed properties of solar wind MHD fluctuations are characteristically interpreted in two distinct ways: either as large amplitude noninteracting Alfvén waves (3) or as quasi-steady MHD turbulence. While the radial variation of the fluctuation energy from 1–10 AU follows the WKB r^{-3} scaling rather closely (11) suggesting noninteracting waves (14), the radial evolution of the correlation scale is inconsistent with a WKB expansion. The observed proton temperature profile (15, 16), which is flatter than the expected adiabatic law, suggests deposition of turbulence energy as heat. An actively turbulent interplanetary plasma can maintain a powerlaw inertial range, while the low frequency end of the inertial range migrates towards still lower frequencies with increasing heliocentric distance (17, 18). This corresponds, through the frozen-in flow condition, to an increasing correlation scale (see figure), usually attributed (19) to dynamical communication of turbulent eddies to steadily increasing scales.

A cascade process transports energy from the largest interacting turbulent structures to the smallest dissipative scales where it is deposited as heat (5, 6, 7, 8, 9, 10, 11, 12, 13). We compare the results of a recent theoretical treatment of the cascade and heating problem with observations recorded by the Voyager 2 spacecraft from 1 AU to beyond 30 AU. Specifically, we adopt predictions from a theory based on the dynamics of large-scale "eddies," which, when controlled by a single similarity scale, drives a cascade that supplies thermal energy to the plasma. We compare these results with the observed magnetic energy density, magnetic correlation scale, and thermal ion temperature.

THEORY

To develop a tractable model for the radial evolution of MHD-scale solar wind turbulence, we view the fluctuations *locally* as nearly incompressible (20), strongly nonlinear and homogeneous (5, 7). Treatment of strong local turbulence on the same footing as spatial transport is mandated (5, 19, 21) by the similar magnitude of the expansion time $\sim r/U$ and the eddy-turnover time $\sim \lambda/u$ (U denotes the large-scale flow speed, and u the rms turbulent velocity). To a first approximation, transport of turbulent fluctuations involves advection and propagation in prescribed large-scale plasma flow and magnetic fields. MHD turbulence transport equations are derived using an assumption of scale separation ($\lambda/r \ll 1$), thereby generalizing WKB theory (7, 22) and leading to evolution equations for various correlation functions (7, 8) involving the Elsässer variables $\mathbf{z}_\pm = \mathbf{v} \pm \mathbf{b}$, where $\mathbf{v}$ is the turbulent plasma velocity and $\mathbf{b}$ the fluctuating component of the magnetic field in Alfvén units.

A simplified theory which uses the Taylor–von Kármán approach (23, 24) can be derived which describes the evolution of hydrodynamic turbulence from the perspective of the "energy-containing eddies". This description requires an energy u^2 and an associated similarity length scale λ. A distinguishing feature of the MHD case, with a locally uniform mean magnetic field $\mathbf{B}_0$ is the appearance of anisotropy (25, 26, 27, 28, 29) associated with suppressed spectral transfer in the direction parallel to $\mathbf{B}_0$. For simplicity, we postulate that spectral transfer is of the quasi-2D or nearly "zero frequency" type, usually described by reduced MHD (20, 29, 30, 31). Accordingly, for low cross helicity ($\mathbf{v}$ and $\mathbf{b}$ uncorrelated) the theory takes the form:

$$\frac{dZ^2}{dr} = -\frac{A'}{r}Z^2 - \frac{\alpha}{U}\frac{Z^3}{\lambda} + \frac{\dot{E}_{PI}}{U}, \tag{1}$$

$$\frac{d\lambda}{dr} = -\frac{C'}{r}\lambda + \frac{\beta}{U}Z - \frac{\beta}{U}\frac{\lambda}{Z^2}\dot{E}_{PI}, \tag{2}$$

$$\frac{dT}{dr} = -\frac{4}{3}\frac{T}{r} + \frac{2}{3}\frac{m_p}{k_B}\frac{\alpha}{U}\frac{Z^3}{\lambda} \tag{3}$$

where $Z^2 = \langle v^2 + b^2 \rangle$ is the energy density expressed in Elsässer variables and T is the thermal ion temperature. $U = 400$ km/s is the solar wind speed and r is the heliocentric distance. The remaining parameters: A', C', α and β, are heavily constrained by rotational symmetry, Taylor–Kármán local phenomenology, and solar wind conditions. $\dot{E}_{PI}$ is the energy injection rate due to pickup ions which we define in the next section. λ may be associated with a correlation scale transverse to the mean field (35) given by $\int_0^\infty R(r', 0, 0)\,\mathrm{d}r' \equiv L = \lambda Z^2$ where R is the 2-point autocorrelation function for magnetic fluctuations. An alternate e-folding definition for λ is that separation distance where $R(\lambda^e) = R(0)/e$. A more detailed description of the theory is available (33). Z^2, λ, and T will be compared to observations in the following section.

COMPARISON WITH OBSERVATIONS

The observations presented here were obtained by the Voyager 2 spacecraft from launch in 1977 through 1998. Spacecraft noise and the low interplanetary field intensity forces us to only consider magnetic field measurements made prior to 1990.

The magnetic power measurements are derived from 10-hour means and variances of the N component (in heliocentric RTN coordinates). The N component is free of the magnetic field reversals associated with the IMF sector structure (heliospheric current sheet crossings) which would provide a false power contribution to estimates of the fluctuations and are difficult to remove effectively. The resulting radial variation is averaged over 50 consecutive estimates to smooth the local variability in the IMF power. Possible time dependence in the solar source for IMF energy and thermal ion temperatures is removed using 1 AU observations by the Omnitape dataset for the corresponding interval, taking into account the appropriate time lag for convection.

The magnetic correlation length is computed using only the N component. A 30-hour maximum lag is used to estimate the integrated and e-folding correlation lengths which are separately averaged over 50 consecutive estimates. The thermal ion temperature was smoothed by the instrument team. A 1 AU normalization of the temperature data was performed (not shown) and confirms the conclusions given here.

We need to select values for solar wind conditions at 1 AU that we will hold constant throughout the radial evolution of the turbulence, enabling us to then compare only the radial variation derived from the theory with the observed radial variation of the interplanetary turbulence. We will assume that $Z^2 = 250$ km^2/s^2, $\lambda = 0.04$ AU and $T = 7 \times 10^4$ K, which are in good agreement with the observations.

Two separate comparisons with the observations are made. First, we set the magnetic energy injection due to pickup ions to zero and examine the evolution of the turbulence driven by wind shear alone. Then we add the influence of pickup ion energy injection and observe the improved agreement with observations from the distant outer heliosphere.

Without Pickup Ions: We assume that the turbulence is driven entirely by shear with $C_{sh} = \hat{C}_{sh} = 2$. We plot the observed magnetic energy (top panel), the correlation length (middle panel) and the ion temperature (bottom panel) as measured by Voyager 2 and compare with the turbulence transport predictions using the above parameterization. Predictions of this theory are represented by solid lines in all three panels. The shear-driven turbulence model gives a good prediction for the radial dependence of the magnetic energy level to $\sim$ 10 AU, but at greater distances the observed energy appears to consistently exceed the predicted level. The predicted and observed correlation lengths agree reasonably well with the theoretical predictions through the entire range of observations and it is interesting that both the integrated and e-folding definitions agree well with each other. The solar wind ion temperature exhibits greater variation than the magnetic quantities, but here, too, the theory and observations agree well out to $\sim$ 10 AU. Beyond this distance, both the observed magnetic energy and ion temperatures consistently exceed the predicted levels.

With Pickup Ions: The second case includes energy input due to wave excitation by pickup ions (32), a process that becomes important in the outer heliosphere. The pickup energy input scales as $\dot{E}_{PI} \sim f_D v_A U n_H / \tau$, where n_H is the density of interstellar neutrals, τ is their ionization time and $f_D = 0.04$. The theoretical results continue to include the shear source, but beyond $\sim$ 10 AU this term is weakened and largely ineffective. The theoretical predictions with pickup ion driving are represented in the same figure by dashed lines. From 1 to $\sim$ 10 AU there is little difference from the first case. However for $r \gtrsim 10$ AU there are notable effects associated with pickup ions. The predicted turbulence level is slightly higher (top panel), and in somewhat improved accord with the data, while the predicted similarity scale begins to decrease (middle panel), an effect not seen in the Voyager data. (This behavior is the result of a limitation imposed by the $\alpha = \beta$ assumption that requires the conservation law $Z\lambda =$ const. We suspect this artifact may be eliminated by generalizing the model to include two components – quasi-2D fluctuations and parallel propagating waves – but we defer this to future work.) On the other hand the temperature prediction from the theoretical model with pickup ions appears to account for the Voyager proton temperatures very well (bottom panel). There is a clear rise in the ion temperature beyond $\sim$ 30 AU that is accounted for with the incorporation of the pickup ion source.

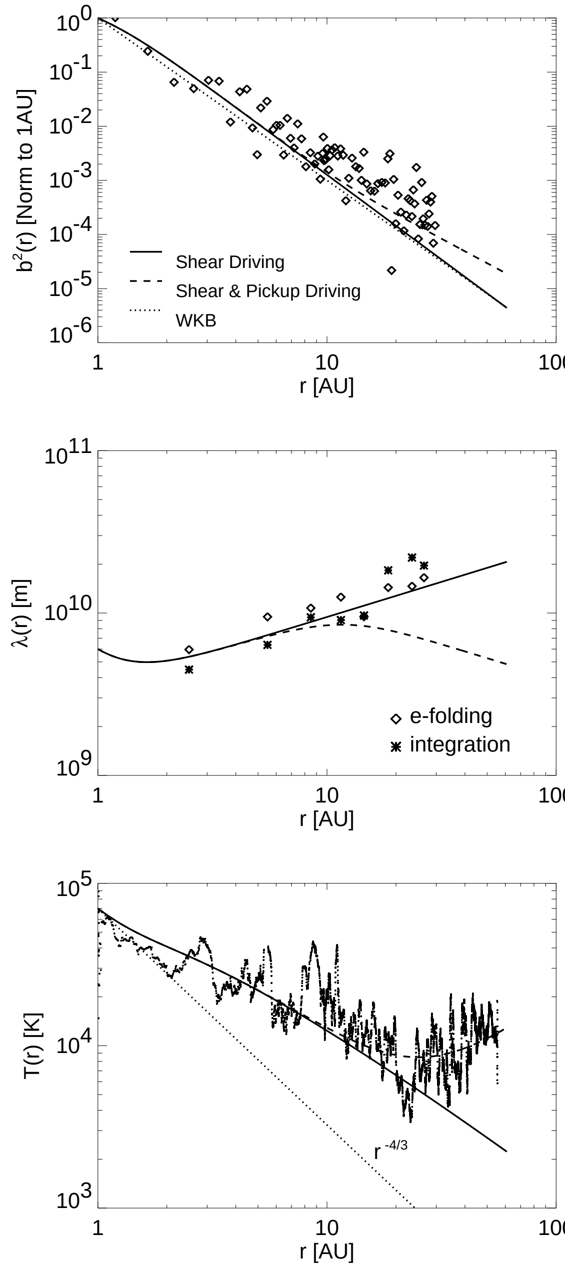

FIGURE 1. *Top panel*: The observed radial dependence of the IMF power normalized to 1 AU. Theoretical prediction of this theory using shear driving alone (solid line) and shear plus pickup ions (dashed line) and the predictions of WKB theory (dotted line) are also shown. *Middle panel*: The radial evolution of the correlation lengthscale as determined from both the integrated and e-folding definitions are compared with the predictions of this theory for shear driving alone (solid line) and shear plus pickup ions (dashed line). *Bottom panel*: The observed radial variation of the thermal ion temperature compared with shear driving (solid line) and shear plus pickup ions (dashed line). The dotted line shows the prediction of adiabatic expansion.

SUMMARY

The simple turbulence model outlined above accounts well for the baseline interplanetary turbulence properties observed by the Voyager 2 spacecraft from 1 AU to several tens of AU. For the first time a theory provides a concise explanation for the average behavior of key parameters that describe solar wind fluctuations. Evidently the heating of the solar wind observed beyond 20 AU cannot be explained by shear driven turbulence alone. Driving by injection of wave energy associated with pickup ions (32) works well at a theoretical level, thus encouraging further searches for the associated waves which have so far remained observationally elusive. The present result also provides substantial support for two theoretical assertions: (*i*) solar wind turbulence is dynamically active, and not a passive remnant of coronal processes; and (*ii*) an MHD nonlinear Kármán–Taylor approach to turbulent heating is defensible and at least moderately accurate, in a form that neglects Alfvén wave propagation effects (34).

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